MakerSat-0: 3D-Printed Polymer Degradation First Data from Orbit

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ABSTRACT

Northwest Nazarene University (NNU) undergraduate engineering students and faculty designed and built Idaho's first CubeSat, MakerSat-0, which NASA launched into orbit on Nov. 18, 2017 from Vandenberg AFB aboard a Delta II rocket. MakerSat-0 was one of five CubeSats chosen by NASA in 2016 for the ELaNa XIV mission. It is the first in a series of proof-of-concept missions that will demonstrate the advantages of on-orbit manufacturing, assembly, and deployment of CubeSats from the International Space Station (ISS). This project is in collaboration with Made In Space, makers of the ISS 3D printer. For the past nine months, MakerSat-0 has been operating in a sun-synchronous polar orbit with a 97min period, 830km x 480km, an inclination of 97.71 degrees, and LTAN of 13:20. It has already travelled 110million miles in 3900 orbits and is expected to orbit for at least eight years. MakerSat-0 hosts two onboard experiments: an ionizing radiation particle counter built by Caldwell High School (CHS) students and a 3D printed polymer degradation experiment built by NNU students. Four different 3D printed polymer samples (ABS, Nylon12, PEI/PC, and PLA) are being exposed to long term spaceflight and are experiencing ongoing erosion and mass loss due to monoatomic oxygen radicals, outgassing, extreme temperatures, ultraviolet (UV) radiation, solar & cosmic ionizing radiation, and even micrometeor impacts. A novel vibrational cantilever test system was designed by the NNU team to continuously measure fractional mass losses from these polymer samples over a long time period in the harsh space environment. This will determine which materials are adequately robust for future use in 3D printed spacecraft. Early orbital data from this polymer degradation experiment shows that mass loss occurs at different rates from these various polymers, with the most robust (least mass loss) also being the densest material, PLA. Radiation data and satellite health data are analyzed, producing key lessons learned that have already been applied to the upcoming MakerSat-1 mission.

MOTIVATION AND OVERVIEW

The 3D printer onboard the ISS opens up a unique opportunity to manufacture, assemble, and deploy small satellites, all while in space. Microgravity additive manufacturing (also known as 3D printing) of small satellite frames on-orbit using polymer materials is advantageous over traditional aluminum metal frames due to:

- Reduced mass
- Freedom to design unique geometries
- Availability to be manufactured in space

However, CubeSat frames made of polymers have potential problems for space application. The first is that polymer frames might undergo structural failure under the large stresses occurring during launch. The second is that polymers might undergo mass loss and structural erosion in the orbital space environment for the duration of the CubeSat mission. The first problem can be addressed by manufacturing the frame onboard the ISS and avoiding the launch stresses all together. The second problem is the motivation for the MakerSat-0 polymer degradation experiment described in this paper. The goal of this experiment is to characterize the mass loss of several 3D printed polymers over time so that the most robust polymer materials can be chosen for use in future spacecraft, and so that appropriate structures can be designed that tolerate the mass loss intrinsic to polymers in space.

NNU and Made in Space are currently engaged in the MakerSat-1 follow up mission, which will be assembled onboard the ISS using a snap-together polymer frame that was 3D printed there, together with a set of six electronic boards shipped there on a resupply flight. MakerSat-1 utilized the data collected from MakerSat-0 to choose the right polymer material. The MakerSat-1 frame was 3D printed aboard the ISS and displayed in the cupola window as seen in Fig. 1. The MakerSat-1 flat-sat "flower-petal" assembly of six electronic boards, is shown in Fig. 2. A video was created to show the astronaut crew how to perform the simple five minute snap-together assembly, with no screws, tools or adhesive: www.youtube.com/watch?v=shLPETczsF4 Fig. 3 shows the MakerSat-1 mission concept.

Fig 1. MakerSat-1 frame 3D printed onboard the ISS

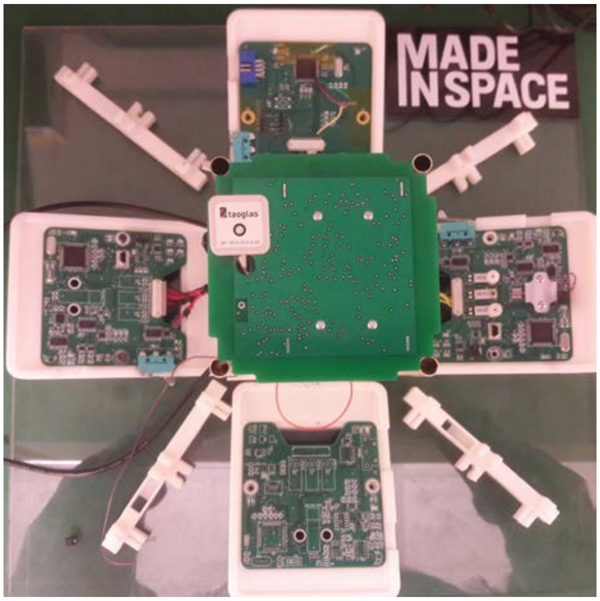
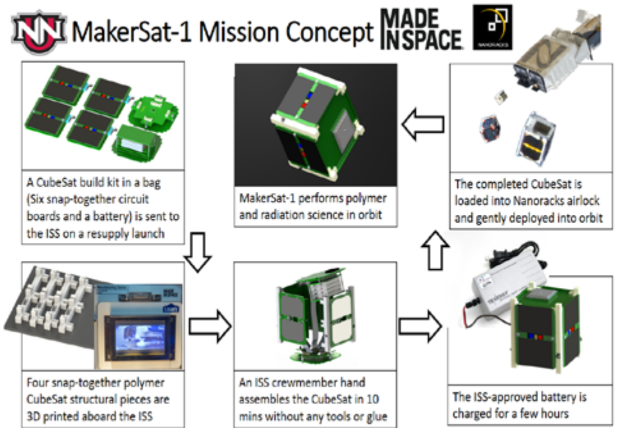


Fig 2. MakerSat-1 electronic board “flower-petal” ready for shipment to ISS and snap-together assembly by the crew.



A CubeSat build kit in a bag (Six snap-together circuit boards and a battery) is sent to the ISS on a resupply launch

Four snap-together polymer CubeSat structural pieces are 3D printed aboard the ISS

An ISS crewmember hand assembles the CubeSat in 10 mins without any tools or glue

The ISS-approved battery is charged for a few hours

The completed CubeSat is loaded into Nanoracks airlock and gently deployed into orbit

MakerSat-1 performs polymer and radiation science in orbit

Fig 3. MakerSat-1 mission concept

MAKERSAT-0 HARDWARE DESCRIPTION

MakerSat-0 utilized a 1U FastBus aluminum box structure from Near Space Launch (NSL) as shown in Fig. 4. It is quite robust and passed two rounds of shock testing plus the actual launch. Five of its six sides are covered with solar panels containing two triple-junction GaAs solar cells each, separated by a center science window slot, through which the polymer test samples, radiation sensor, RBF pin, and diagnostic ports protrude, directly exposed to the external space environment.

The NSL EPS/radio/battery unit is on the Y- side and the NNU/CHS science payload is on the Y+ side. The X, Y, and Z- solar cells are connected to provide 3.5V, 0.4A, 1.4W into a boost circuit that charges the two LiPo 7.4V batteries to a total capacity of 4.4Ah. The Z+ side has both transmitter and receiver radio patch antennas for Globalstar. A pre-launch photo of MakerSat-0 is shown in Fig. 5.

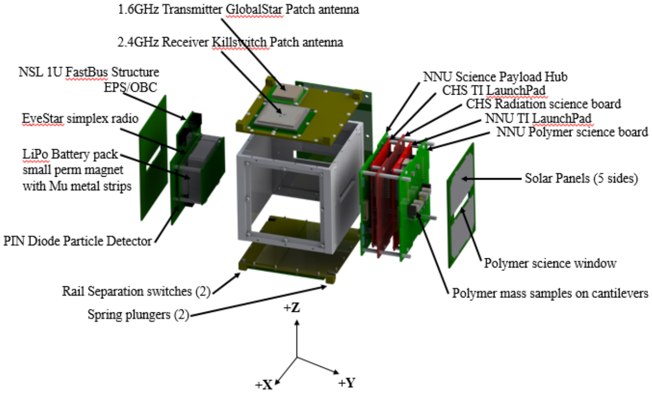


Fig 4. MakerSat-0 exploded diagram

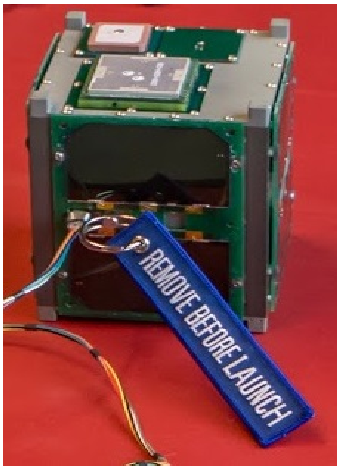


Fig 5. MakerSat-0 pre-launch photo

The NSL EPS/OBC board uses a radiation-tolerant 8-bit PIC microcontroller with extensive flight history including TSAT, GEARRS1, and GEARRS2. The satellite uses a small permanent magnet and orthogonal mu-metal dampening strips as passive attitude control to slowly orient its Z axis to the Earth's polar magnetic field lines.

Most CubeSats use ground station radio uplinks to send commands to the satellite and radio downlinks to send data from the satellite. Such grounds stations often operate in the VHF and UHF amateur bands. The design and operation of a ground station adds significant cost and complexity to CubeSat mission planning and operations. To avoid these issues, MakerSat-0 utilizes an EyeStar simplex radio from NSL, which communicates between the CubeSat and GlobalStar's LEO satellite constellation, using an SMS text messaging protocol. This "bent-pipe" communication method provides a 24/7 data downlink to several ground receiving gateways located around the globe, tied to a secure NSL data server, from which the NNU and CHS students can view near-real-time (2 minute latency) health and science data from MakerSat-0 on their smartphones and laptops anytime, anywhere. The low data rate of 3Bps is adequate for MakerSat's small data volumes.

The NNU polymer and CHS radiation science experiment boards each utilize an ultra-low-power Texas Instruments MSP430 microcontroller "LaunchPad" development daughter board, containing radiation-tolerant, non-volatile FRAM memory. These two science boards are connected to a "Science Hub" board designed by NNU, providing shared control, data processing/buffering and radio communication to the science boards in a round-robin fashion.

SATELLITE HEALTH DATA

MakerSat-0 began sending voltage and temperature health beacon data packets only 50 minutes after deployment, transmitting four 36 byte beacon packets every 90 minutes. MakerSat-0 is the first satellite using a GlobalStar radio to be placed in a polar orbit, so the packet reception over the frequently traversed polar regions that have fewer satellites and gateways was unknown prior to this mission. During the first 200 mission days, 3200 beacon packets were transmitted, but only 394 complete packets were received (12%). It was observed from the partial packets received that the data reception rate would be improved to the 90% range if the packets were made half as long (18 bytes).

The first beacon data received after the Nov. 18 launch showed that the two Y solar cells were no longer functional, and were probably cracked at launch due to mechanical or thermal shock. This reduced the solar energy collection capability of the satellite by 40%, making each orbit negative with respect to the power budget. With no radio command uplink ability, we were unable to use less power per orbit. So, the battery gradually discharged from 9.1V down to 6.5V on Dec. 3, as shown in Fig 6a. At this trigger voltage, the satellite went into safe mode and stopped doing science. However, the safe mode was not safe enough to allow the battery voltage to fully recharge before restarting science, so the battery voltage continued to fall down to the current range of 5.2-6.2V, as shown in Fig. 6b. A gradual downward trend in average battery voltage is ongoing and will result in satellite failure at some point below 5V. In this battery voltage range, the satellite OBC microcontroller reboots after every sunlit recharge period and then tries to perform 16 consecutive health beacon packet radio transmits. However, due to this high radio power consumption, the battery voltage rapidly depletes back to the reboot level again before it is able to complete these 16 packet transmits. So the satellite is in an infinite "solar-locked" rebooting loop, probably rebooting once every orbit, or 15 times a day. Nevertheless, we are continuing to receive several health beacon packets per day.

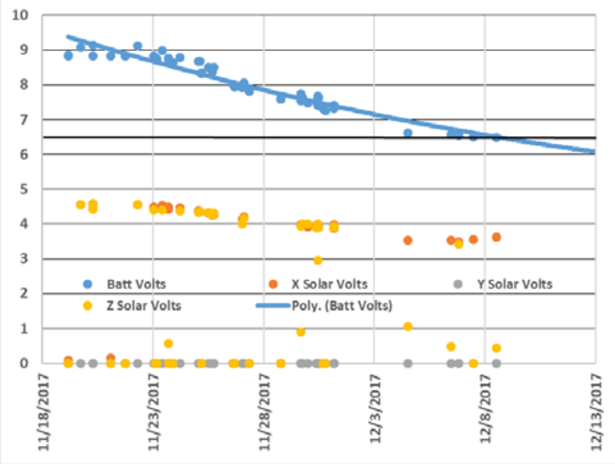


Fig 6a. Battery & Solar Voltages vs. Time (first 2 weeks)

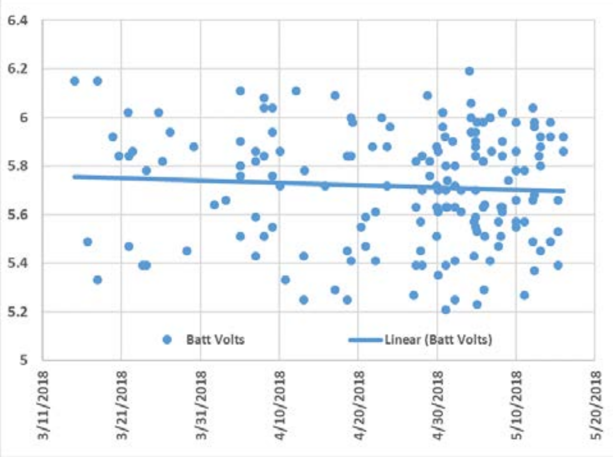


Fig 6b. Battery Voltage vs. Time (solar-locked state)

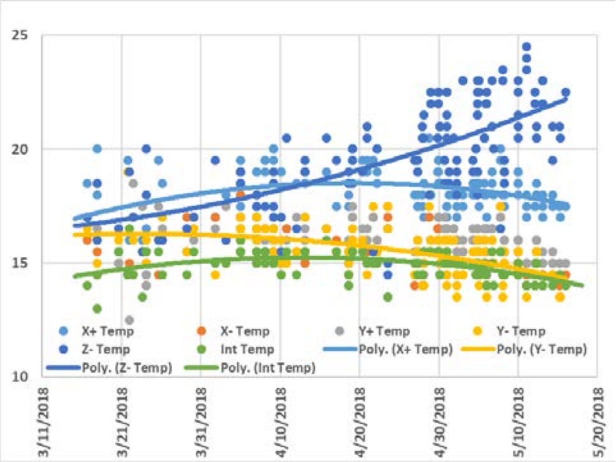


Fig 7. Temperatures (C) vs. Time (solar-locked state)

The X,Y,Z surface temperatures and internal temperature varied from -15C in eclipse to +25C in sunlight on MakerSat-0, before it became "solar locked." Now that it is solar locked, it is active only in the sunlight. Fig. 7 shows the temperatures of the various solar panels and the internal temperature vs. time. It appears that the passive attitude control magnet is gradually stabilizing the Z- surface toward the sun, causing it to heat to 22C, 5 to 7 degrees warmer than the other surfaces which are becoming cooler.

IONIZING RADIATION EXPERIMENT DATA

The Caldwell HS science experiment board contained a PIN diode radiation particle detector coupled with an MSP430 microcontroller counter circuit to measure the ionizing radiation particle flux rate inside the shielded aluminum satellite cube, as shown in Fig. 9. Most of the time this flux rate was nearly zero, but it was considerably higher when passing through the polar auroras or the SAMA and fluctuated over its 60sec measurement period. Unfortunately, few Globalstar data packets were received from the polar aurora regions, but some were received from the SAMA region locations as mapped in Fig. 8.

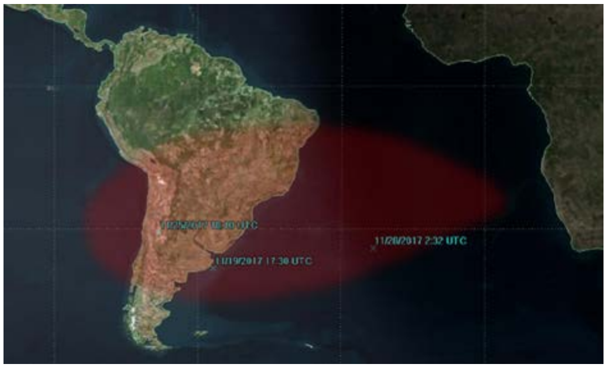


Fig 8. Locations in SAMA where higher flux was observed

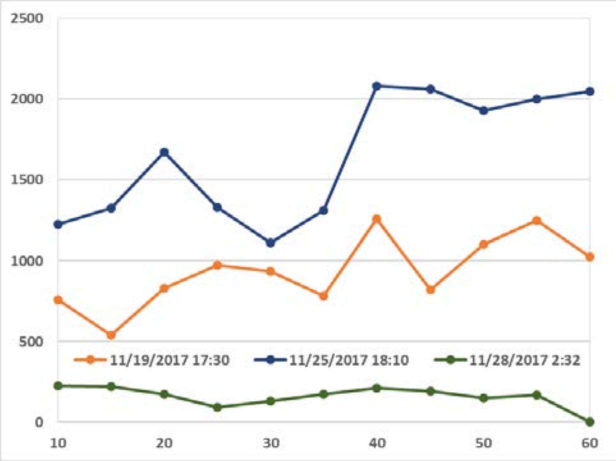


Fig 9. Radiation Flux (particles/sec) over a 60sec period

POLYMER EXPERIMENT DESIGN

Erosion and structural degradation of polymers in space happens via monoatomic oxygen radicals, ultraviolet solar radiation, ionizing solar & cosmic radiation, outgassing in vacuum, extreme hot and cold temperatures, and even micrometeorite erosion. The MakerSat-0 polymer experiment measures the in-space mass losses of four 3D printed polymers: Nylon12, ABS, PLA, and PEI/PC. To quantify the different mass loss rates, an experiment was designed to continuously measure the mass of each polymer sample over time during the eight-year orbit. It uses five piezo-resistive cantilever beams, each with a different tiny cylindrical polymer sample mass mounted to the end of its beam. One cantilever beam is left unloaded as a reference and used to isolate the polymer mass loss from the effects of space on the sensor itself. These polymer mass samples are directly exposed to the space environment through a small window slot in the satellite exterior. The PCB on which these five cantilevers are mounted is excited by a small excitation source (vibration motor) over a 40-100Hz frequency range. The natural damped frequency of each cantilever is measured after the forced vibration ceases. This resonant frequency is known to be inversely proportional to the square root of the mass on the end of the beam (see Eq. 1), allowing precise indirect measurement of milligram mass losses, even in microgravity.

$$f_{res} = \frac{1}{2\pi}\sqrt{\frac{3EI}{L^3 m}} \quad \text{[Eq. 1]}$$

where f_{res} is the resonant frequency of the cantilever beam, E is Young's modulus of the cantilever beam, I is the moment of inertia of the cantilever beam, L is the length of the cantilever beam, and m is the total mass on the end of the cantilever beam (sum of a brass button and the polymer sample).

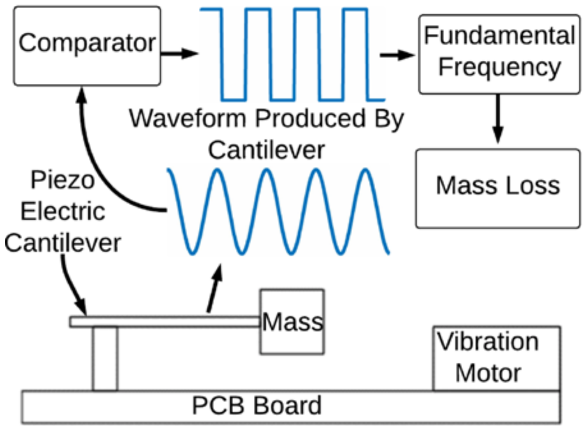


Fig 10. Polymer degradation experiment block diagram

Fig. 10 is a diagram of the polymer experiment. The piezoelectric cantilevers provide an output voltage proportional to the deflection of the cantilever beam. The cantilevers and the vibration motor are mounted in close proximity on a rigid PCB. When the vibration motor excites the cantilever, it produces a damped sine wave. The sine wave is then transformed through a comparator into a square wave, while maintaining the same fundamental frequency. The fundamental frequency of the square wave is then measured by the on-board microcontroller using the capture registers in its timer module. The cantilever's response at the resonant frequency is then used to determine the mass of the 3D printed polymer, according to theory. It is important to note that the experiment is done differentially, with respect to the unloaded control cantilever with a brass button that does not degrade over time in orbit, thus eliminating systematic common mode error. Fig. 11 is a drawing of the experiment, showing the location of the different components.

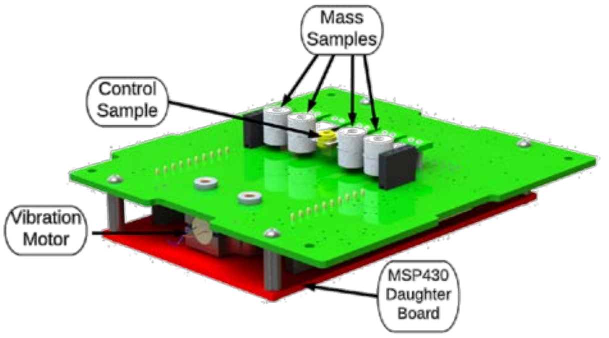


Fig 11. Drawing of the polymer mass loss experiment

3D POLYMER DEGRADATION DATA

We received 877 data packets from MakerSat-0 between its Nov. 18 launch and Dec. 3, 2017, when its battery voltage level dropped below the 6.5V necessary to operate the science experiments. This represents about 10% of the packets that were transmitted, similar to the beacon packet reception rate. Fig. 12 is an example of a cantilever waveform measured during orbit. The waveform pictured came from the brass control cantilever.

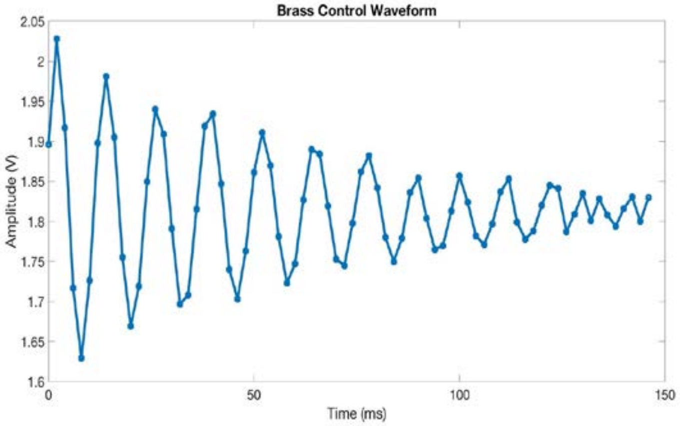


Fig 12. Raw waveform of cantilever captured during orbit

Each polymer pre-flight mass and resonant frequency was measured in the lab in 1G at room temperature and standard atmospheric pressure. Since the samples were 3D printed with the same volumes, their pre-flight masses correlated directly with their various densities:

	Brass	ABS	Nylon12	PEI/PC	PLA
Density (g/cm3)	0	1.04	1.06	1.2	1.24
Preflight frequency (Hz)	87.4	NA	62.4	55	54.6
Preflight total mass (mg)	337	581	587	636	687
Preflight poly mass (mg)	0	246	251	293	354
Initial frequency (Hz)	89.4	NA	69.4	57.3	56.6
Normed initial frequency	87.4 (+0%)	NA	67.4 (+8.0%)	55.3 (+0.5%)	54.6 (+0%)
Normed final frequency (Hz)	87.4 (+0%)	NA	68.6 (+9.9%)	58.6 (+6.5%)	54.6 (+0%)
Initial mass loss (mg)	0 (-0%)	NA	84.0 (-33.4%)	6.0 (-2.0%)	0 (-0%)
Final mass loss (mg)	0 (-0%)	NA	101.0 (-40.3%)	50.0 (-17.0%)	0 (-0%)

Table 1. Polymer degradation data from orbit

Unfortunately, the ABS cantilever stopped working a few days before satellite delivery and produces no useful data in orbit. Data from the first mass measurements made immediately after the satellite launched showed an immediate increase in frequency for the reference cantilever and all the cantilevers, due to the combined effects of microgravity, space vacuum, and particularly the lower temperature making the cantilevers stiffer. This initial frequency increase was normalized out of all the cantilevers. The PLA sample showed no frequency or mass loss changes. However, the PEI/PC frequency increased by 0.5%, indicating a mass loss of 6 mg (2.0%) while the Nylon frequency increased by 8.0%, indicating a mass loss of 84 mg (33.4%). This suggests that the PEI/PC and the Nylon samples experienced outgassing mass loss right after launch, while the PLA sample did not.

After 15 days of orbit, the final data received from the experiment on Dec. 3, 2017 showed that the PLA frequency and mass were still stable (no loss) while the Nylon had lost an additional 17mg and the PEI had lost an additional 44mg. It may or may not be accurate to extrapolate these mass loss rates to longer orbital time periods. The large initial mass loss of Nylon, but small ongoing mass loss rate is contrasted with the small initial mass loss of PEI, but its unusually large ongoing mass loss rate. The resonant frequencies of all the cantilevers show a high (10%) sensitivity to orbital temperature swings of 30C (from -15C to +15C), which required us to use onboard temperature measurements to compensate this data, in order to accurately extract the polymer mass losses. The interesting conclusion from our data is that the mass loss rate correlates roughly with the density of the polymer. The most robust (least mass loss) was PLA, which is the densest. The least robust (most mass loss was Nylon, which is the least dense, and PEI/PC Ultem is in between.

MAKERSAT-1

As mentioned previously, the MakerSat concept will be fully demonstrated with MakerSat-1. MakerSat-1 will be printed, assembled, charged, tested, and deployed from the ISS in late 2018. MakerSat-1 uses a simple snap-together design that can be completed in approximately five minutes, without the use of any adhesive or free-floating fasteners or tools. The three MakerSat-1 science boards contain repeats of the MakerSat-0 CHS radiation and NNU polymer experiments, as well as a new sponsoring corporate experiment.

LESSONS LEARNED

First, we learned than excellent PCB ground plane and decoupling capacitor design must be used to avoid excessive electrical noise in a CubeSat running on only battery, without a large stable power supply. Our I^2C circuits such as a 9DOF IMU did not work due to the noisy environment created by our vibration motor. We decided to switch to SPI circuits in the future, which are less noise sensitive. We also learned to test the CubeSat earlier on battery only, not depending on large external power supplies or USB programmers to stabilize the power rails. We learned that standard UTJ solar cells are very fragile, and launch-induced cracks can drastically reduce the energy collection capability of a CubeSat, leading to battery discharge. On MakerSat-1, we are switching to flexible, durable ALTA solar cells. We learned to add several smarter layers of contingency safe modes which will allow for graceful recovery from low power or radiation-induced reboots. We have learned that shorter 18byte packets are needed for adequate GlobalStar communication over the polar regions. These improvements have been implemented on MakerSat-1.

SUMMARY

We are now entering the era of designing and building small satellites and spacecraft on-demand, in-space, instead of being bound to Earth’s surface and atmosphere. The outcome will be new degrees of freedom in spacecraft design and in-space manufacturing with reduced costs, reduced development times, and greater creativity and access for students.

ACKNOWLEDGEMENTS

Thanks to Dennis Zattiero and his students at Caldwell HS, Matt Napoli and his team at Made In Space, Jeff Dailey and his team at NearSpaceLaunch, the NASA LSP and Tyvak ELaNa XIV team, Dave Pahlas and his team at Plexus, and to Idaho Space Grant Consortium.

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